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Supercontinuum generation in ICP-CVD silicon-rich silicon nitride waveguides

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Abstract. Inductively coupled plasma chemical vapor deposition was used to obtain thin films of silicon-rich silicon nitride with a refractive index of 2.44 at optical telecommunications wavelength. The resulting layer was patterned into a 1.6 μm wide waveguide and tested for its nonlinear behavior using a 90-fs all-fiber laser centered at 1630 nm. A significant spectral broadening is demonstrated with a supercontinuum generation from 1300 nm to 1985 nm. Simulations are in fair agreement with the experiments, assuming a nonlinear index of $2 \times 10^{-18} \text{ m}^2/\text{W}$.

1 Introduction

Integrated photonic components use waveguides to carry information signals at optical wavelengths, typically from the visible to the near-infrared region. Materials such as silicon [1], silica [2], and silicon nitride [3] are commonly used in photonic integrated circuits (PICs) to reduce their footprint and power consumption. The selection of materials depends on application requirements. Typically, for materials used in nonlinear on-chip applications, high linear and nonlinear refractive indices combined with low or negligible two-photon absorption are requested [4]. While stoichiometric silicon nitride is currently the most common material due to its low attenuation, alternative materials such as Ta_2O_5 [5], TiO_2 [6], and silicon-rich silicon nitride (SiRN) [7] with higher nonlinearity have appeared. In this contribution, we focused our attention on the latest. Indeed, as shown in Table 1, this platform is a promising tradeoff between silicon and stoichiometric silicon nitride. Our goal is to optimize the waveguide dimensions in order to demonstrate the on-chip generation of a supercontinuum starting from an ultrashort fiber laser.

| | Silicon | Si_3N_4 | SiRN |
|----------------------------------|---------|-------------------------|---------|
| Index n (@1.55 μm) | 3.47 | 2.0 | 2.3-2.7 |
| n_2 (x fused silica) | 125 | 10 | 80 |
| TPA (cm/GW) | 0.9 | Negligible | <0.10 |

Table 1. Comparison of material properties

2 Waveguide design and fabrication

Among the processes have been tested to deposit SiRN layers, we have selected the Inductively Coupled Plasma Chemical Vapor Deposition (ICP-CVD) method. The refractive index of SiRN layers we manufactured is measured by ellipsometry and is shown as a function of wavelength in Figure 1.

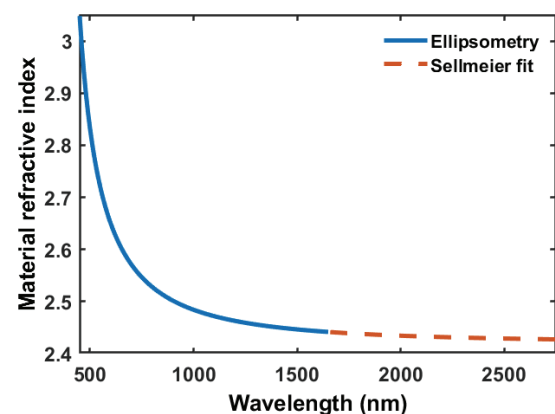


Figure 1. Ellipsometry measurement for SiRN layers (blue line) with Sellmeier fit extrapolation beyond 1650nm (red dashed line)

Once the refractive index is known, the linear and nonlinear properties such as the mode effective index and the corresponding dispersion or the effective area can be numerically derived from numerical simulations (homemade code based on wg modes [8]). Optimizing the nonlinear coefficient alone at telecommunication wavelengths would direct us to a waveguide height between 250 and 350 nm (considering a width higher than 1 μm because of the UV lithography process used in fabrication). In that case, effective areas below 1 μm^2 can be reached. However, such thickness leads to all-normal dispersion which is not the most advantageous for an ultra-broadband supercontinuum. In order to reach the regime of anomalous dispersion, one should increase the thickness of the waveguide (see, Fig. 2(a) obtained at a fixed width of 1.6 μm). As shown in the panel (b) of Fig. 2, increasing the width of the waveguide (here with a fixed height of 570 nm) mainly affects the position of the two zero dispersion wavelengths. Note that the second zero dispersion wavelength is beyond 2.4 μm (which is the limit of the optical spectrum analyzer used in the next section).

Accordingly, the selected dimensions targeted were a height of 570 nm and a width of 1.6 μm for the waveguide. During the deposition process on the ICP-CVD, we used a temperature of 350°C, a pressure of 18 mTorr, and an ICP power of 2000 W. After 23 minutes with 330 sccm of SiH_4 (5% diluted in He), 9 sccm of N_2 and 30 sccm of Ar, a 570 nm thick layer is produced. The AZ MiR 701 UV-

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sensitive resist layer was patterned using I-line patterning followed by reactive ion etching to form a 1.6 μm wide waveguide.

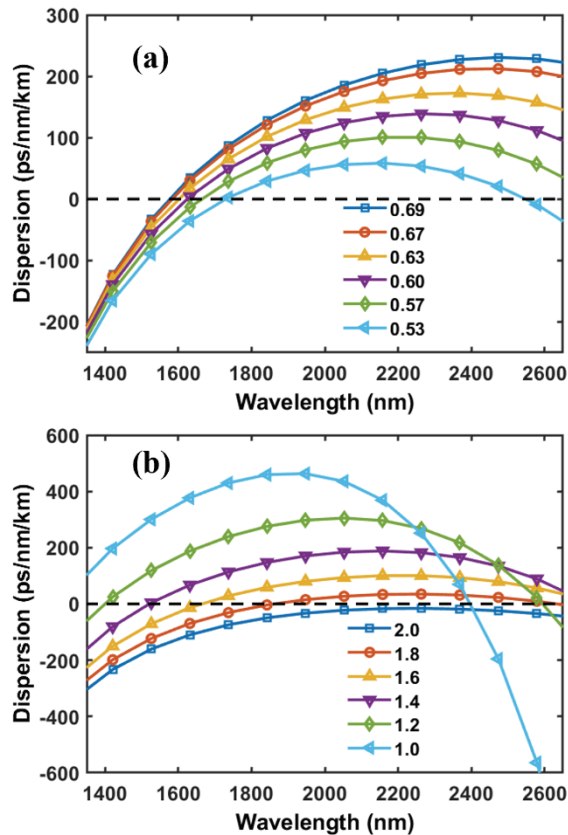


Figure 2. Numerical simulations of the spectral evolution of the dispersive properties of the SiRN waveguides. (a) Influence of the waveguide height, the width being kept constant to 1.6 μm (b) Influence of the waveguide width, the height being kept constant to 0.57 μm .

3 Continuum generation

Lensed fibers were used to inject a 90-fs all-fiber laser centered at 1630 nm at an 80 MHz repetition rate into the waveguide to test its nonlinear behavior. At the output, the light is analyzed thanks to an optical spectrum analyzer (OSA) working up to 2.4 μm .

Figure 3(a) shows the output spectral properties of the pulses. A significant spectral broadening of the input pulse can be observed with a supercontinuum spanning over 600 nm, from 1300 nm to 1985 nm (at -40 dB) for an input launched power of 8 mW.

Simulations based on numerical integration of the generalized nonlinear Schrodinger equation predict the broadened spectrum shown in Fig. 3(b) which is in fair agreement with the experiments.

4 Conclusion

Our work confirms that the silicon-rich silicon nitride is an interesting nonlinear platform. At this stage, the supercontinuum generated is similar to the state of the art on this material [7]. However, several improvements can

be done regarding the dispersion with, for instance, a second zero dispersion wavelength closer to 2 μm . We believe that after improvements, we should be able to reach the mid-infrared region.

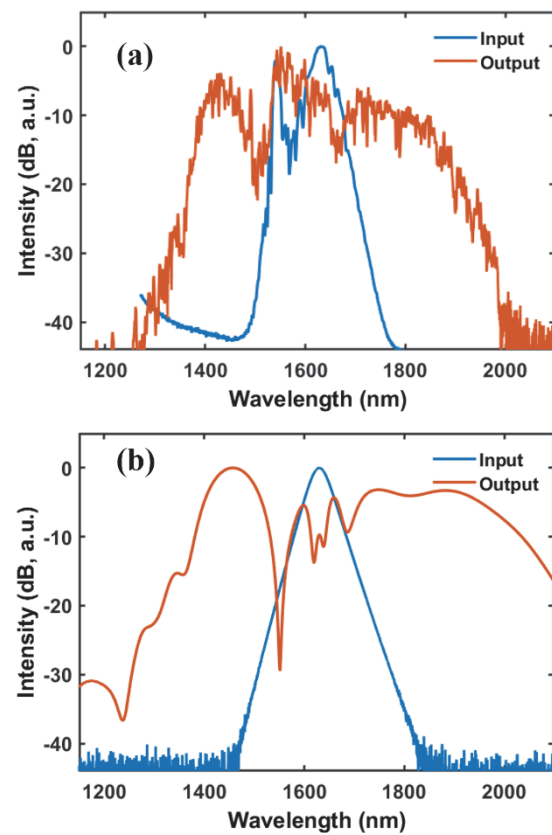


Figure 3. (a) Comparison of the spectrum of the input fs laser and the output light collected on OSA. (b) Corresponding simulation.

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